eRHIC Plans Update

- ERL-Ring eRHIC design
- ERL-Ring vs. Ring-Ring design
- eRHIC R&D plan summary
- Next version of ERL-Ring design
- Summary of path forward

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eRHIC R&D Advisory Committee
April 7 – 8, 2016

BROOKHAVEN
NATIONAL LABORATORY

a passion for discovery

Office of Science
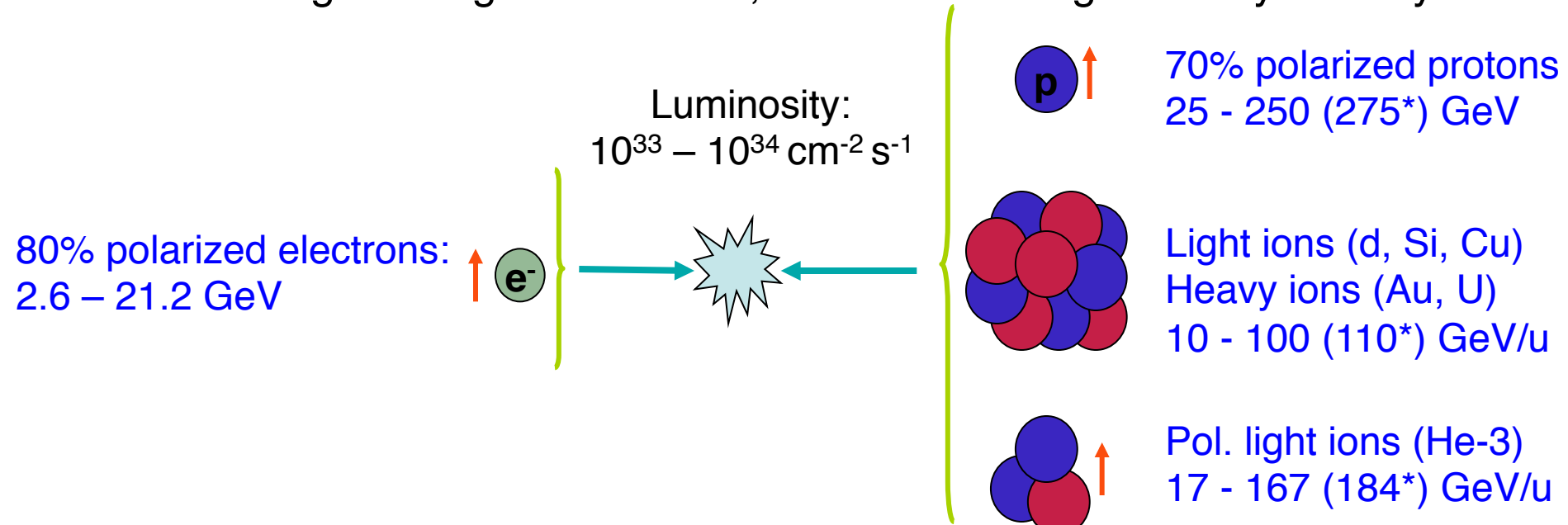U.S. DEPARTMENT OF ENERGY

Charge for this meeting

- Evaluate the technical design maturity of each option (linac-ring and ring-ring)

- Evaluate, for each proposal (LR or RR), whether or how the technical risks could be sufficiently retired by early 2018 to make the design the basis of a project proposal to DOE at that time.

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC
including existing RHIC tunnel, detector buildings and cryo facility

Luminosity:
$10^{33} - 10^{34}$ cm^{-2} s^{-1}

p   70% polarized protons
25 - 250 (275*) GeV

80% polarized electrons:
2.6 – 21.2 GeV

e⁻

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

Pol. light ions (He-3)
17 - 167 (184*) GeV/u

- Center-of-mass energy range: 20 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
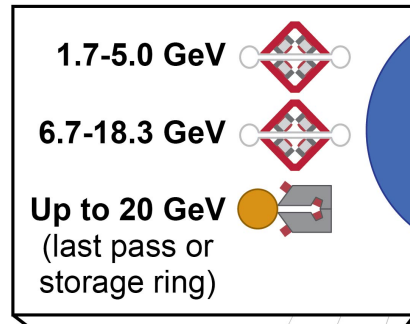- Any polarization direction in electron-hadron collisions:
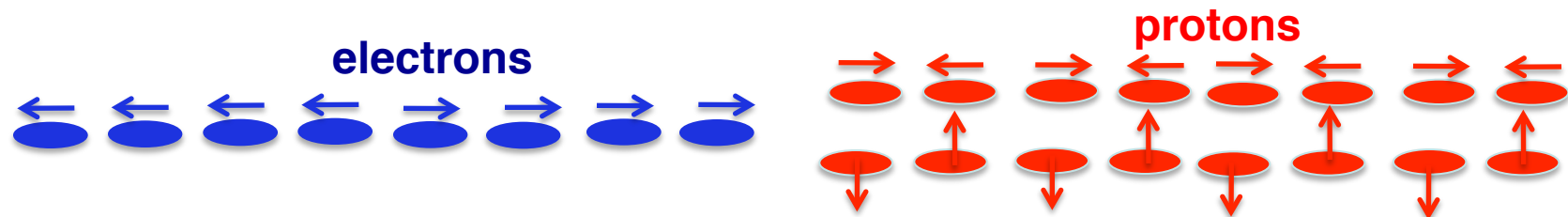
protons

electrons

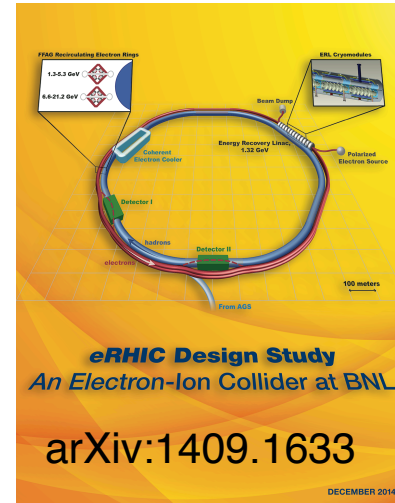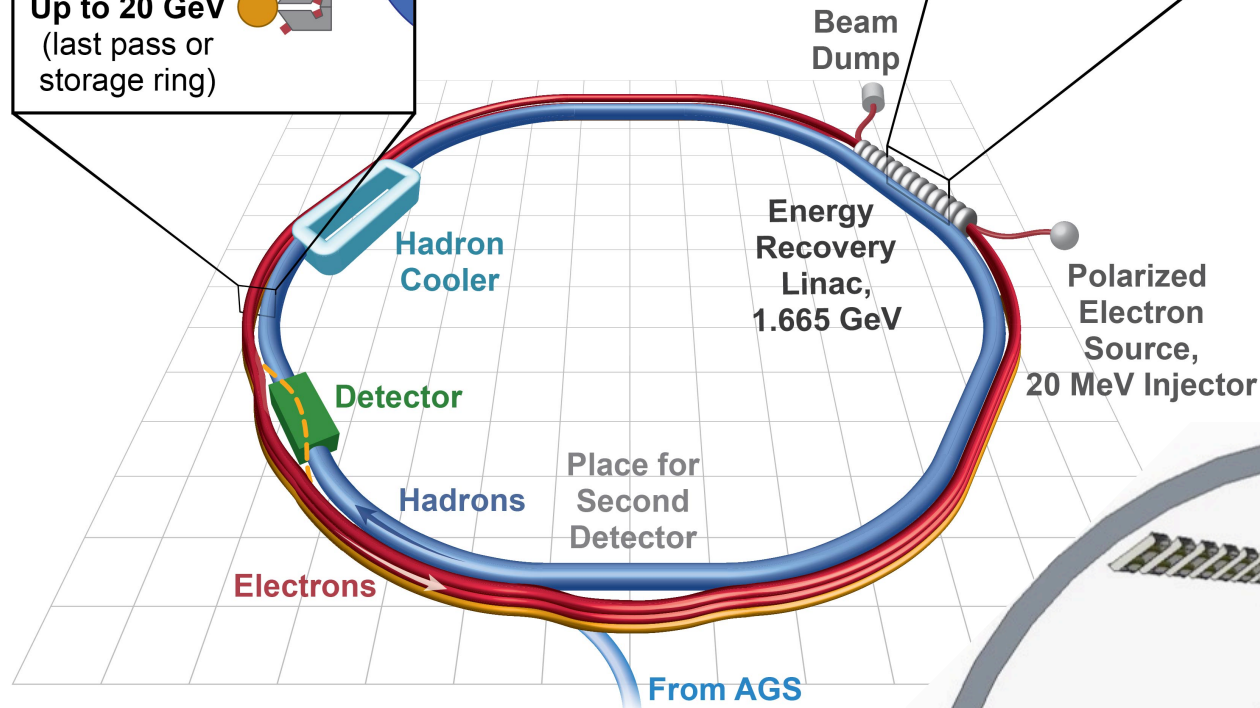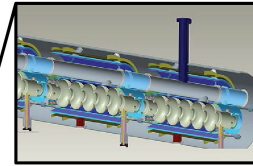* It is possible to increase RHIC ring energy by 10%

eRHIC design
Highly advanced and energy efficient accelerator

Electron Beamlines

1.7-5.0 GeV

6.7-18.3 GeV

Up to 20 GeV
(last pass or
storage ring)

ERL Cryomodules

Beam
Dump

Energy
Recovery
Linac,
1.665 GeV

Hadron
Cooler

Detector

Place for
Second
Detector

Hadrons

Electrons

From AGS

Polarized
Electron
Source,
20 MeV Injector

eRHIC Design Study
An Electron-Ion Collider at BNL

arXiv:1409.1633

DECEMBER 2014
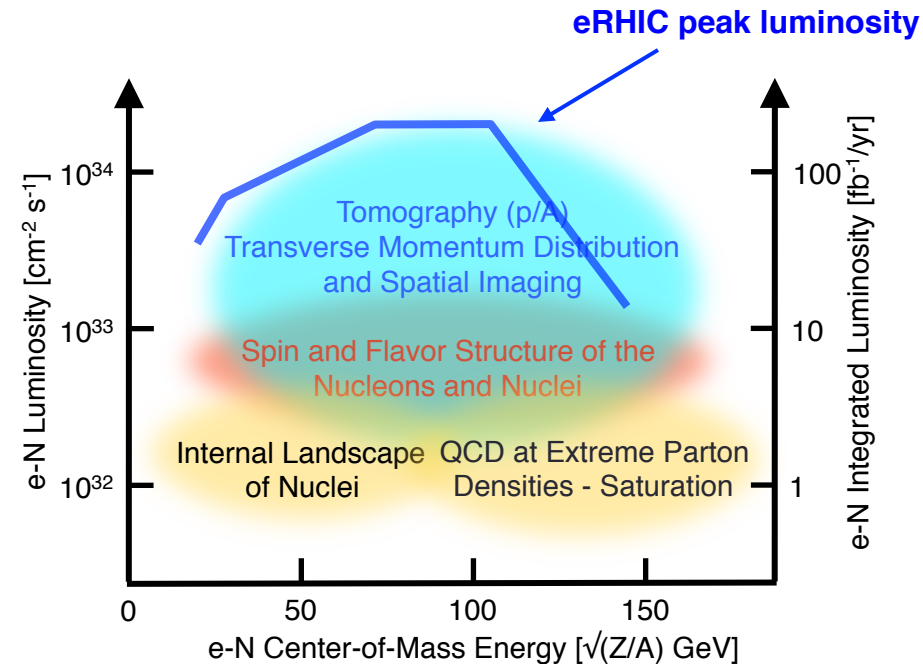
- Peak luminosity: 2×10^{34} cm^{-2} s^{-1}
- ERL, permanent magnet arcs and strong cooling of proton beam greatly reduce electric power consumption to about 15 MW!
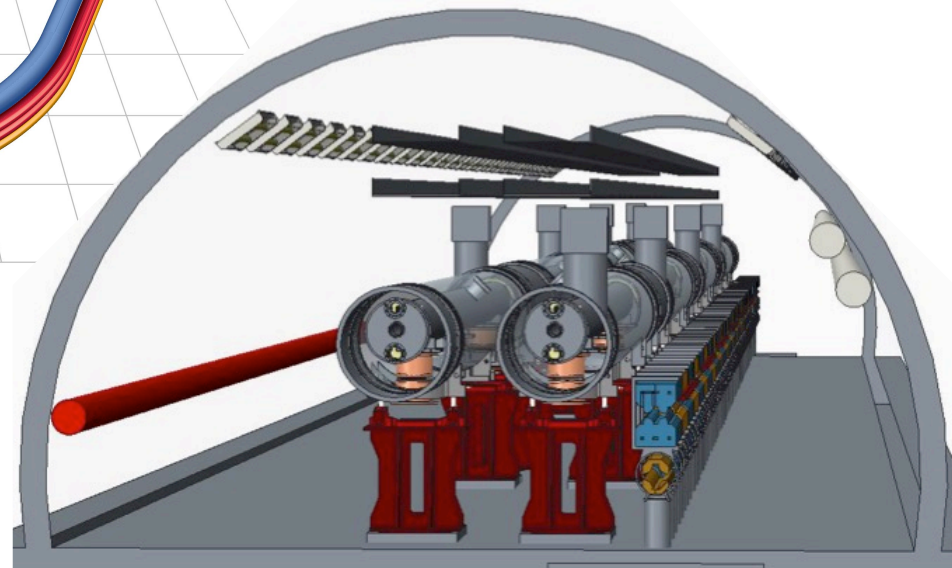
eRHIC peak luminosity vs. CoM energy
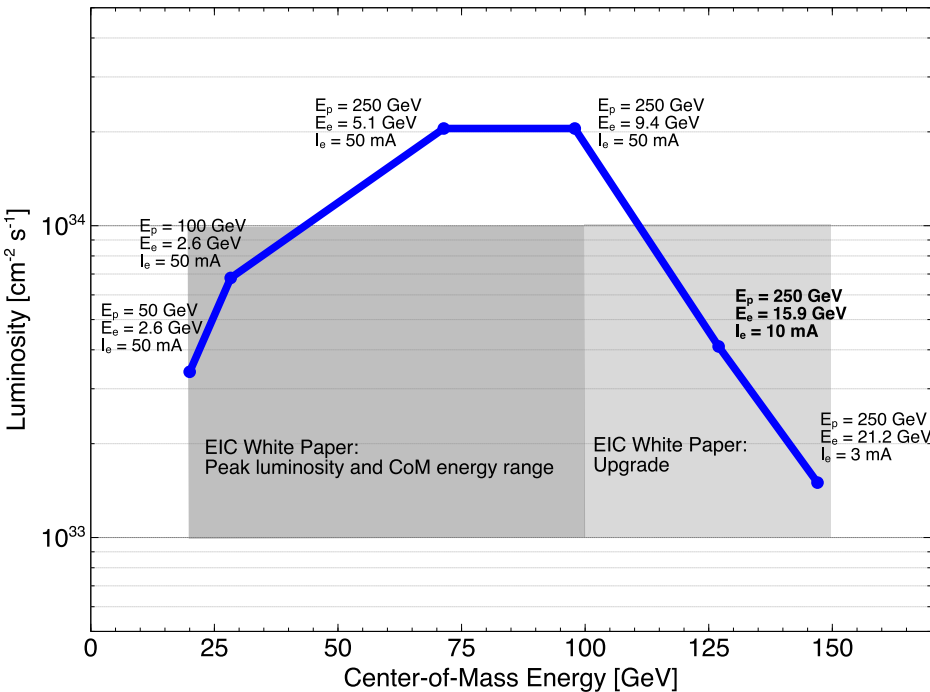
- eRHIC design covers whole Center-of-Mass energy range, including "EIC White Paper Upgrade" region
- Small beam emittances and IR design allows for full acceptance detector at full luminosity

Ring – ring vs. ERL – ring

$$L = f_b \left(\frac{4\pi\gamma_p\gamma_e}{r_p r_e} \right) \left(\xi_p \xi_e \right) \left(\sigma'_p \sigma'_e \right) \qquad \xi_p = \frac{r_p \beta^*_p}{4\pi\gamma_p} \frac{N_e}{\sigma^2_e} \qquad \xi_e = \frac{r_e \beta^*_e}{4\pi\gamma_e} \frac{N_p}{\sigma^2_p}$$

$$\frac{4\pi\gamma_p\gamma_e}{r_p r_e} = 2.7 \cdot 10^{36} \ cm^{-2} \qquad \sigma'_p = \sigma'_e \le 0.15 mrad \quad \xi_p \le 0.015 \qquad \xi_e \le 0.1$$

for E_p=250 GeV, E_e=20 GeV

for ring - ring

- Ring – Ring
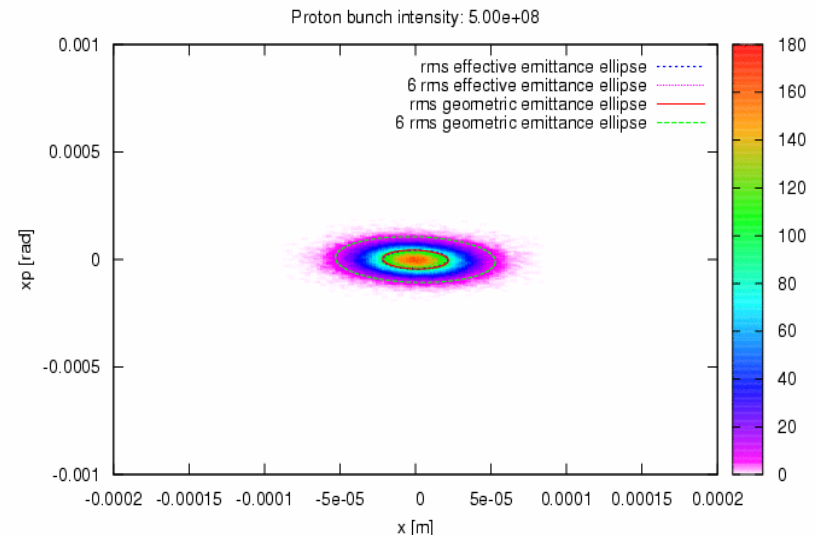 - For bunch rep. rate f_b = 10 MHz: $L \le 9 \times 10^{32}$ s^{-1} cm^{-2}
  - Increase luminosity by increasing f_b (and electron current and synchrotron radiation power)
  - Decrease electron current (and synchrotron power) by **cooling proton beam** and use low emittance electron storage ring
  - High synchrotron radiation in detector and arcs is the main challenge

- ERL – Ring
  - For bunch rep. rate f_b = 10 MHz (or any rate) the luminosity is not limited; eRHIC design study had ξ_e=1.5: $L = 1.4 \times 10^{34}$ s^{-1} cm^{-2}
  - Increase luminosity and/or decrease electron current by **cooling proton beam**
  - Source with high polarized electron current is the main challenge

High luminosity with a Linac-Ring collider

- For Linac-Ring collider the single collision of electron bunch removes the limitation of the beam-beam effect of the high energy hadron beam on the lower energy electron beam

- Can reach high luminosity with high intensity, low emittance hadron beam and lower intensity electron beam (and less synchrotron radiation power)

- Disruption of electron beam by hadron beam is large (similar to ILC) but emittance growth is limited due to the focusing by the hadron beam (pinch effect)

- Need strong hadron beam cooling (10 times in transverse and longitudinal direction) for highest luminosities, small vertex distribution, and small forward divergence

- Novel cooling method:
  - Coherent electron Cooling (CeC)
  - Required performance demonstrated in extensive simulations
  - Proof-of-Principle test underway at RHIC

Proton bunch intensity: 5.00e+08
rms effective emittance ellipse
6 rms effective emittance ellipse
rms geometric emittance ellipse
6 rms geometric emittance ellipse

eRHIC TPC cost elements

WBS	eRHIC	FY15 M$				
		Burdened Labor	Burdened Material	Cont. $	Total	Cont. %
1.1	Civil Construction/Infrastructure	7.3	40.8	18.9	**67.0**	39%
1.2	Cryogenic Systems	12.2	47.5	16.0	**75.7**	27%
1.3	CW SRF Linac	23.4	69.6	36.8	**129.8**	40%
1.4	RF Power Amplifiers and LLRF	3.2	47.9	15.6	**66.7**	30%
1.5	Magnets	22.8	66.7	27.7	**117.3**	31%
1.6	Vacuum	9.9	45.3	11.0	**66.2**	20%
1.7	Magnet PS	3.1	31.6	11.5	**46.1**	33%
1.8	Instrumentation	13.2	23.2	10.6	**47.0**	29%
1.9	Controls	9.8	7.3	5.4	**22.4**	31%
1.10	Electron Injector and Abort	7.2	14.1	7.2	**28.5**	34%
1.11	RHIC Modifications	6.7	6.2	4.0	**17.0**	31%
1.12	Commissioning/Pre-Operations	6.9	7.8	4.3	**18.9**	29%
1.13	Project Management/Control	21.3	2.4	4.7	**28.4**	20%
1.14	Project R&D	20.0	10.8	9.2	**40.0**	30%
	TPC Total	**167.1**	**421.1**	**182.9**	**771.1**	**31%**

- Full bottom-up cost and contingency estimate of eRHIC conceptual design

- WBS elements 1.1 to 1.11 all include PED, construction, assembly, and installation

- Substantial opportunities for value engineering exist

eRHIC TPC with functional WBS structure

WBS	eRHIC	FY15 M$				
		Burdened Labor	Burdened Material	Cont. $	Total	Cont. %
1.1	Civil Construction General	7.3	40.8	18.9	**67.0**	39%
1.2	Cryogenic System Central	10.5	38.2	12.6	**61.4**	26%
1.3	Electron Injector	7.6	19.9	9.3	**36.7**	34%
1.4	Main SRF Linac (1.3 GeV)	18.4	74.9	32.0	**125.3**	34%
1.5	Recirculation arcs (2 FFAG)	27.7	111.0	41.1	**179.8**	30%
1.6	Spreader and Combiner sections (16 beam lines)	5.1	19.0	6.8	**30.9**	28%
1.7	Electron beam abort	1.6	2.0	1.2	**4.8**	34%
1.8	Crab cavities	4.0	15.2	6.8	**26.1**	36%
1.9	Electron Cooling	11.7	44.9	19.2	**75.7**	34%
1.10	Controls Central	9.8	7.3	5.4	**22.4**	31%
1.11	RHIC Modifications including IR	12.8	23.5	11.9	**48.2**	33%
1.12	Commissioning/Pre-Operations	6.9	7.8	4.3	**18.9**	29%
1.13	Project Management/Control	23.8	4.2	5.3	**33.3**	19%
1.14	Project R&D	20.0	10.8	9.2	**40.0**	30%
	TPC Total	**167.1**	**419.4**	**184.1**	**770.6**	**31%**

- Note that arcs cost is higher than Linac cost

Plan for eRHIC design

- Our approach to the eRHIC design to minimize cost and risk:
  - The initial configuration of eRHIC should have enough center-of-mass reach (20 GeV pol. e x 250 GeV pol. p and 20 GeV e x 100 GeV/n Au) and detector acceptance to cover the whole EIC science case.
  - The initial luminosity could be lower and then increased through incremental upgrades, as was done for RHIC and other colliders.
- Present design is the linac-ring option with multi-pass ERL; it follows our approach and can cover the whole EIC physics case. R&D plan to retire the technical risks to avoid cost for back-up options
- Developing luminosity-staged versions of the eRHIC design to minimize initial cost and technical risk
- Two designs are being developed:
  - **Low risk ERL-Ring**: It is expected to have lower cost after risk retirement.
  - **Low risk Ring-Ring**: Based on mainly existing technology. Cost is expected to be higher than the ERL-Ring design.
- Both designs can be upgraded to the ultimate eRHIC design for modest cost.

Pre-project eRHIC R&D Plan

- There are four high priority eRHIC R&D items to be completed by ~ 2018.
  - **Test of polarized electron "Gatling Gun" with two to four cathodes; develop single high current polarized electron source (MIT)**, led by John Skaritka
    - *Demonstrate "Gatling principle" and ~ 10 mA of polarized electron current by 2017*
  - **Test of ERL acceleration cavity with full HOM damping**, led by Wencan Xu
    - *LDRD project to design and construct a 650 MHz 5-cell SRF cavity with high power HOM waveguide damping; back-up: RT beam line HOM dampers*
  - **Complete Coherent electron Cooling PoP test during RHIC runs 16 and 17**, led by Vladimir Litvinenko
    - *Develop classical magnetized electron cooling as back up*
  - **High intensity, multi-pass test-ERL with single recirculation arc to be built using the Cornell high intensity electron injector and CW SRF Linac**, led at BNL by Dejan Trbojevic and at Cornell by Georg Hoffstaetter
    - *Plan to complete the BNL-Cornell FFAG-based test-ERL by ~ 2018 with $25M from NYS Empire State Development Cooperation.*
- Additional eRHIC experimental R&D elements, at a lower priority, are:
  - Development of SRF crab cavities, led by Qiong Wu (part of LARP and HL-LHC)
    - ***Should we elevate this item to the high priority pre-project R&D list? Should we start the development of a new low frequency crab cavity?***
  - Experiment of a multi-turn high energy ERL using CEBAF, led at BNL by Francois Meot and at JLab by Todd Satogata.

High CW current polarized electron gun

- Matt Poelker (JLab) achieved 4 mA polarized e-beam with 6 hours charge lifetime
- More current with effectively larger cathode area and laser spot
- Tests started at MIT with very large cathode area
- Gatling gun principle: multiple guns/cathodes with same charge lifetime
  - Requires fast switching between guns/cathodes
- Gatling Gun Test-stand at SBU:
  - Tests with beam from two cathodes started
- Backup to single Gatling gun: Fast switching between four 12.5 mA guns
- Backup to high current gun: Fast switching between ten 12.5 mA guns

Gatling Gun @ SBU

Large cathode gun @ MIT
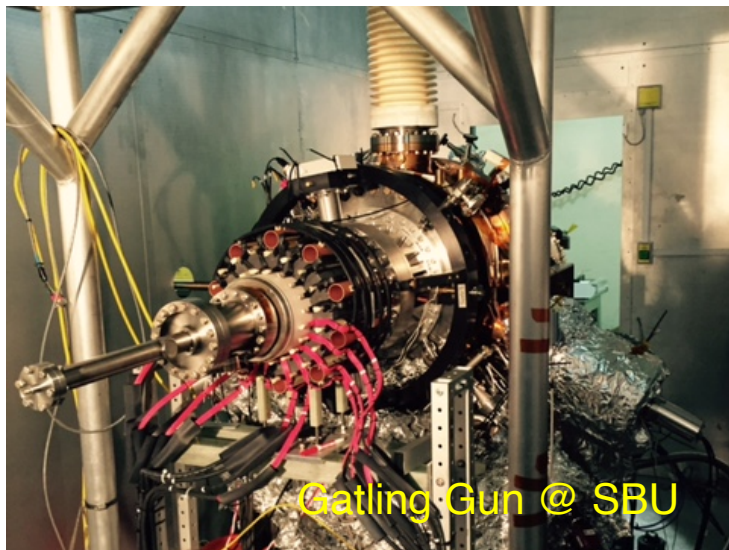
Coherent electron Cooling (CeC) demonstration experiment

- DOE NP R&D project aiming for demonstration of CeC technique is in progress since 2012

- Phase I of the equipment and most of infrastructure installed into RHIC's IP2

- First beam from SRF gun (3 nC/bunch, 1.7 MeV) on 6/24/2015; exceeds performance of all operating CW electron guns

- 20 MeV SRF linac and helical wigglers for FEL amplifier are installed, beam transported to low energy dump

- Proof-of-principle demonstration with 40 GeV/n Au beam scheduled during RHIC Run 16 and 17

- Micro-bunching test also planned with same set-up
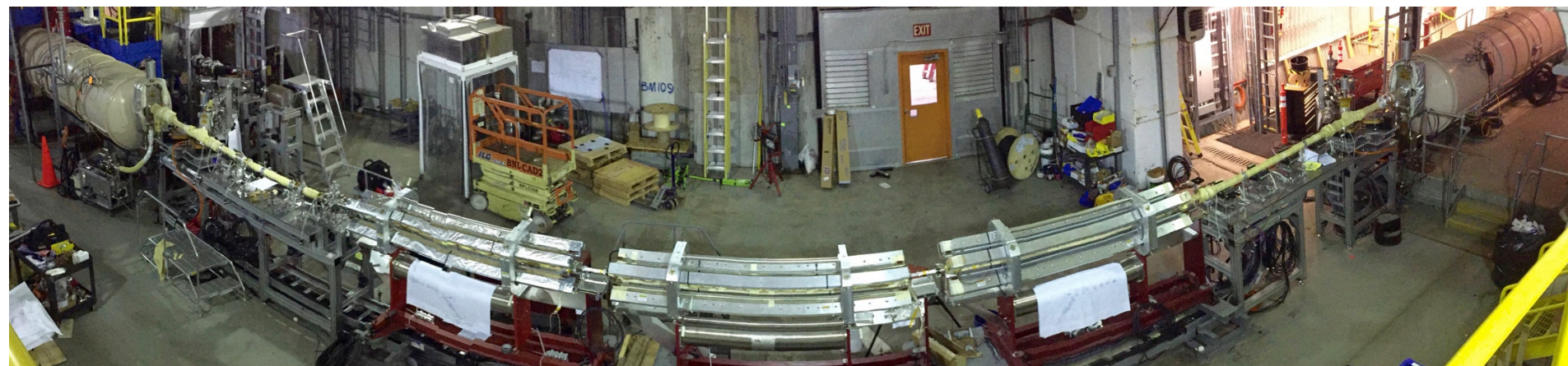
Multi-pass test-ERL at Cornell – an eRHIC prototype

- Uses existing 6 MeV low-emittance and high-current injector and 48.5 MeV CW SRF Linac
- ERL with single four-pass recirculation arc with x4 momentum range
- Permanent magnets used for recirculation arc
- Adiabatic transitions from curved to straight sections
- Test of spreader/combiner beam lines
- High current can be used to test HOM damping by replacing Linac with eRHIC Linac cryostat
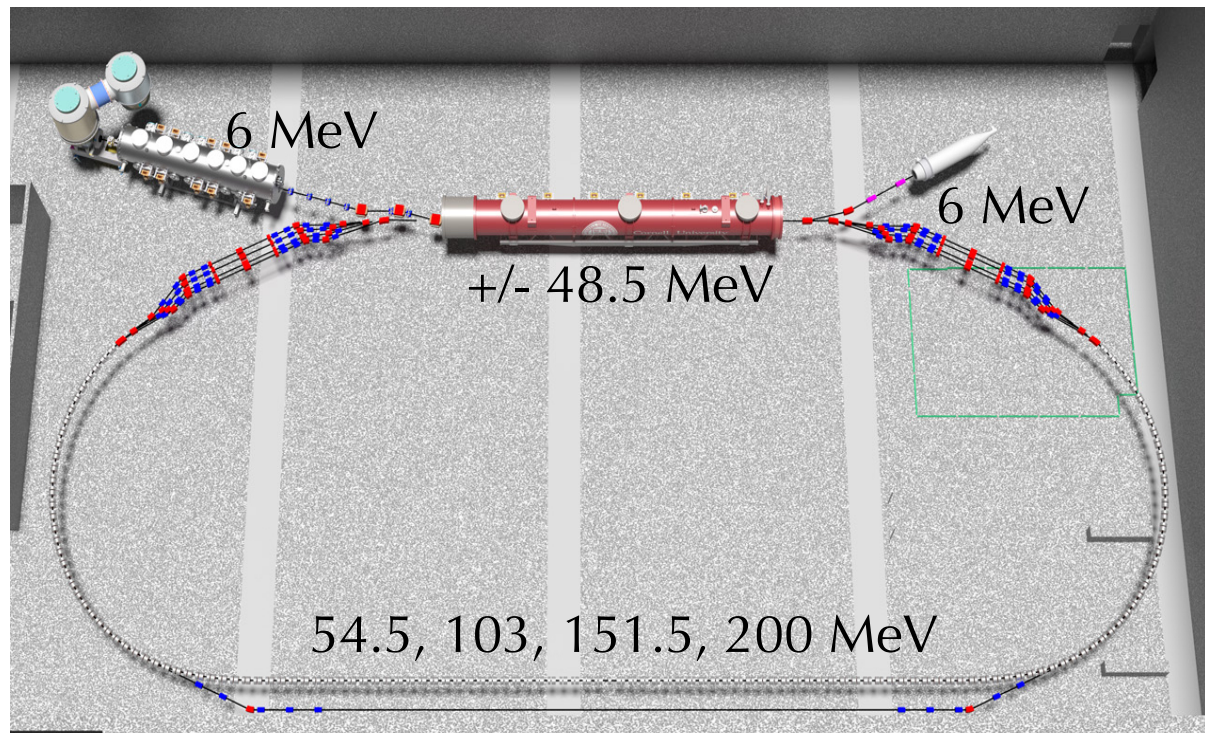
Collaboration network

- We are collaborating with a number of institutions on various aspects of eRHIC R&D. We intend to expand this network.
  - SBU – all R&D items
  - Cornell – FFAG multi-pass ERL experiment, high intensity electron source
  - MIT – polarized gun R&D
  - JLab – CEBAF ERL experiment, possible collaboration on polarized electron gun
  - CERN – crab cavities for HL-LHC and eRHIC (ERL-Ring or Ring-Ring), test-ERL
  - Berkeley – numerical simulations of beam-beam interactions, discuss collaboration on a number of items
  - ANL – discuss collaboration on HOM damper design, possible collaboration on low-energy injector cavities
  - FNAL – possible collaboration on 650 MHz SRF ERL cavities
  - Various SBIR projects – high-efficiency RF amplifiers (completed), in-situ RHIC beam pipe coating (only stage 1), eRHIC permanent magnet development, high intensity electron beam transport

ERL-Ring version 2 (under development)

- 2.5 GeV linac and 7 passes
  - Much reduced total current and HOM power in linac
- 1 FFAG loop with 6 passes and 1 regular last loop
  - Electron energy: 17.5 GeV, RHIC proton energy: 275 GeV, COM energy: 139 GeV
- No energy spread and loss compensators
- Synchrotron power loss ~ 2.5 MW
- No initial hadron cooling, use existing low emittance proton beam in RHIC
 - Ready for installation of cooling as modest upgrade

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1.2	Cryogenic System Central	10.5	38.2	12.6	61.4	26%
1.3	Electron Injector	7.6	19.9	9.3	36.7	34%
1.4	Main SRF Linac (2.5 GeV)	28.8	87.4	40.2	156.4	35%
1.5	Recirculation arcs (1 FFAG, 1 regular)	20.8	83.3	30.8	134.8	30%
1.6	Spreader and Combiner sections (7 beam lines)	2.2	8.3	3.0	13.5	28%
1.7	Electron beam abort	1.6	2.0	1.2	4.8	34%
1.8	Crab cavities	4.0	15.2	6.8	26.1	36%
1.9	Electron Cooling	-	-	-	-	
1.10	Controls Central	9.8	7.3	5.4	22.4	31%
1.11	RHIC Modifications including IR	12.8	23.5	11.9	48.2	33%
1.12	Commissioning/Pre-Operations	6.9	7.8	4.3	18.9	29%
1.13	Project Management/Control	23.8	4.2	5.3	33.3	19%
1.14	Project R&D	20.0	10.8	9.2	40.0	30%
	TPC Total	156.0	348.6	159.0	663.6	32%

Cost of risk mitigation, to be retired by R&D

- ## 50 mA polarized electron current:
  - Back-up: 10 electron guns with fast switching between them (5 mA for 24 hrs. per gun). Required gun performance is close to demonstrated performance (4 mA for 6 hrs.).
  - Additional cost: ~ $50M
- ## FFAG loops:
  - Replace FFAG loop with 6 regular loops
  - Additional cost: 6 * cost [regular loop] – cost [FFAG loop] = ~ $180M
- ## Hadron cooling:
  - No initial hadron cooling
- ## HOM damping of high current CW SRF Linac
  - Use all beam line dampers, demonstrated at KEK-B, instead of waveguide dampers; increases length by about ~ 20%
  - Linac energy reduced from 2.5 GeV to 2 GeV;
  - Electron energy: 14 GeV, RHIC proton energy: 275 GeV, COM energy: 124 GeV
  - Reduced performance but still higher than minimum EIC White Paper requirement (COM energy = 100 GeV)
- ## Total additional cost for risk mitigation: $230M (Total $893.4M)

eRHIC Peak Luminosity vs. CoM Energy

- Science case areas indicate the range of peak luminosities with which a statistically significant result can be achieved in about one year (10^7 sec) of running.
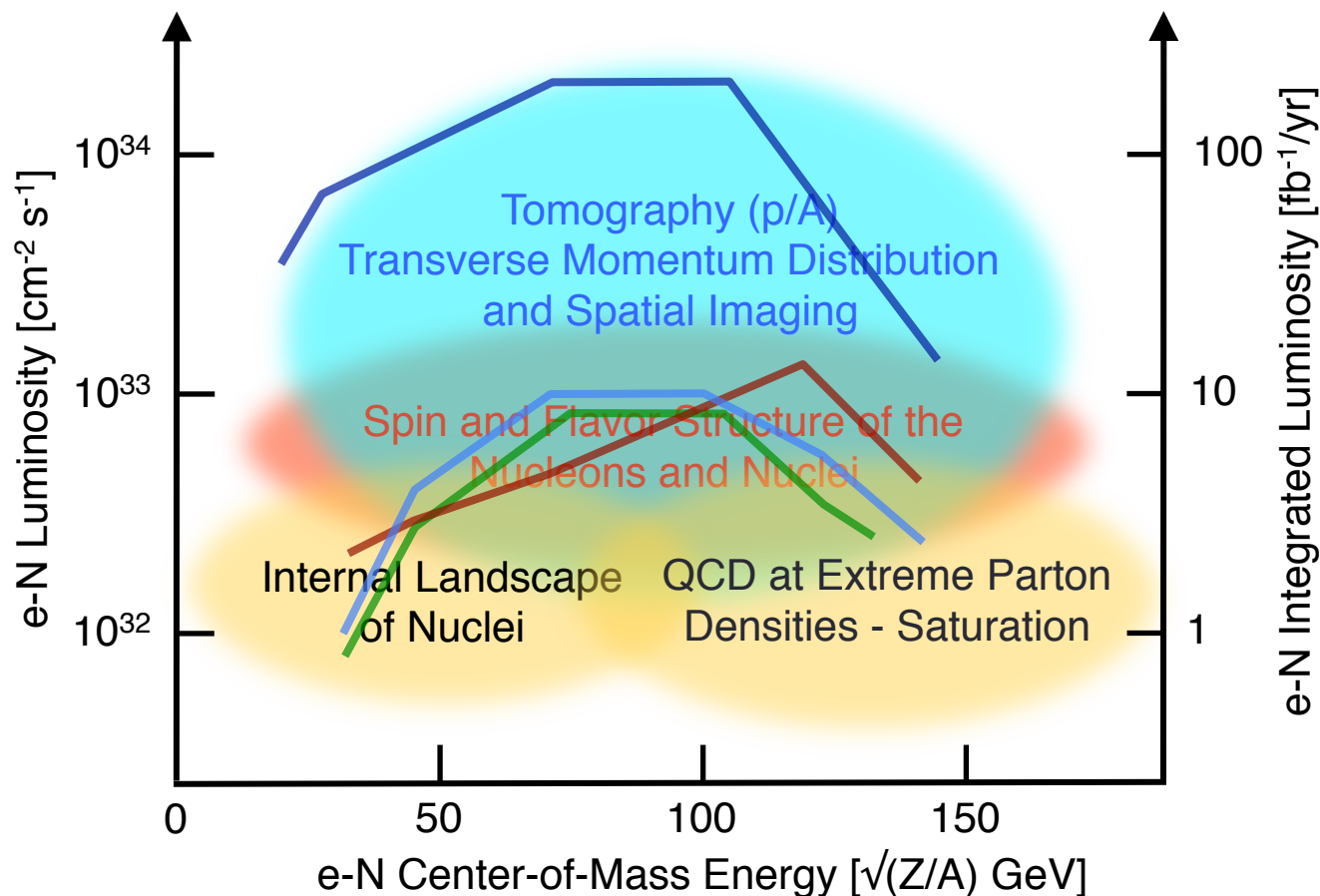
| Ultimate ERL-Ring design | ERL-Ring design, some cooling, $P_{synch} \sim 2.5$ MW | ERL-Ring design, V2, no cooling of protons, $P_{synch} \sim 2.5$ MW | Ring-Ring design, some cooling, 330 bunches, $P_{synch} \sim 10$ MW |

Summary

- Bottom-up cost estimate of eRHIC that covers the complete EIC White Paper science case and is highly cost effective.

- The ERL-Ring eRHIC design combines high performance with unprecedented energy efficiency, an imperative requirement today not only to minimize operations cost but also to conserve resources.

- Developed focused eRHIC R&D plan that addresses all critical technical risks of the eRHIC design over the next 2-3 years:
  - Development of polarized electron source with high total current
  - Test of ERL acceleration cavity with full HOM damping
  - Complete Coherent electron Cooling PoP test during RHIC runs 16 and 17
  - High intensity, multi-pass test-ERL with single recirculation arc to be built using Cornell high intensity electron injector and CW SRF Linac

- Developed cost effective, low risk ERL-Ring and Ring-Ring eRHIC design options with full energy coverage and ~ 10^{33} s^{-1} cm^{-2} luminosity.

- Version 2 ERL-Ring design with lower cost and risk under development

- Cost effective upgrade to ~ 10^{34} s^{-1} cm^{-2} luminosity ERL-Ring design possible for all options.